

# Mobile Phone Faraday Cage

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**Abstract.** A Faraday cage is an interesting physics phenomena where an electromagnetic wave can be excluded from a volume of space by enclosure with an electrically conducting material. The practical application of this in the classroom is to block the signal to a mobile phone by enclosing it in a metal can! The background of the physics behind this is described in some detail followed by a explanation of some demonstrations and experiments which I have used.

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## 1. Static Electromagnetic Fields

A Faraday cage is a hollow enclosure of conducting material (eg. a metal) which blocks out static electric fields. Imagine a static electric field applied to a hollow metal cylinder. The metal cylinder contains charges which are free to move around within the metal. As long as the electric field is applied the charges will move around until they get to the surface of the metal but can then move no further. The charges will collect at the surface and produce an electric field within the metal cylinder which exactly opposes the applied field. This mechanism can be compared with a simple electrical circuit with a 1.5V cell: one side of the cell is at a higher potential than the other so charges move to cancel this out. Thus a static electric field can be excluded from a volume of space by surrounding the space with a conducting material. However, a mobile phone signal is not a static: it is an electromagnetic wave so we now look at the effect of a sinusoidal electric field.

## 2. Sinusoidal Electromagnetic Fields

In the case of a sinusoidal electric field the case is a little more complex. Imagine a simple sinusoidal electromagnetic field whose behaviour is described by Maxwell's equations:

$$\nabla \cdot \mathbf{E} = 0 \quad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2)$$

$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} \quad (3)$$

$$\nabla \times \mathbf{B} = \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \sigma \mathbf{E} \quad (4)$$

where  $\mathbf{E}$  is the electric field,  $\mathbf{B}$  is the magnetic field,  $t$  is time,  $c$  is the speed of light,  $\mu_0$  is the permeability of free space and  $\sigma$  is the electrical conductivity of the metal making up the enclosure. Consider a special type of wave which is an unbounded plane wave. By a plane wave we mean that over planes perpendicular to the direction of the propagation of the wave, all field quantities (such as amplitude, frequency etc.) are constant. By unbounded we mean that the planes are infinite. If the direction of propagation of the wave is taken to be the  $x$  direction, then the wavefronts (or the planes mentioned earlier) are parallel to the  $yz$  plane. This means that the partial differential of  $\mathbf{E}$  or  $\mathbf{B}$  with respect to  $y$  or  $z$  is zero:

$$\frac{\partial}{\partial y} = 0 \quad (5)$$

$$\frac{\partial}{\partial z} = 0 \quad (6)$$

This reduces Maxwell's equations to:

$$\frac{\partial E_z}{\partial x} = \frac{\partial B_y}{\partial t} \quad (7)$$

$$\frac{\partial E_y}{\partial x} = - \frac{\partial B_z}{\partial t} \quad (8)$$

$$\frac{\partial B_z}{\partial x} = -\frac{1}{c^2} \frac{\partial E_y}{\partial t} \quad (9)$$

$$\frac{\partial B_y}{\partial x} = \frac{1}{c^2} \frac{\partial E_z}{\partial t} - \mu_0 \sigma E_y \quad (10)$$

Further, if we choose that the  $\mathbf{E}$  field is along the  $y$  axis then  $E_z = 0$ . This implies that the  $\mathbf{B}$  field is along the  $z$  axis and

$$\frac{\partial B_y}{\partial x} = 0 \quad (11)$$

$$\frac{\partial B_y}{\partial t} = 0 \quad (12)$$

Finally, Maxwell's equation further reduce to:

$$\frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t} \quad (13)$$

$$\frac{\partial B_z}{\partial x} = -\frac{1}{c^2} \frac{\partial E_y}{\partial t} - \mu_0 \sigma E_y \quad (14)$$

$B_z$  (or  $E_y$ ) can be eliminated from the previous two equations to give the wave equation (which is the same in each case):

$$\frac{\partial^2 E_y}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 E_y}{\partial t^2} + \mu_0 \sigma \frac{\partial E_y}{\partial t} \quad (15)$$

Making this relevant to a mobile phone signal we now focus on monochromatic waves (i.e. waves with a single frequency) with the form:

$$E_y(x, t) = E_{y0} e^{i(\mathbf{k}x - \omega t)} \quad (16)$$

where  $i = \sqrt{-1}$ ,  $\mathbf{k}$  is the wave number and  $\omega$  is the angular frequency of the wave. Substituting this into the wave equation above gives us:

$$\mathbf{k}^2 = \frac{\omega^2}{c^2} + i\omega\mu_0\sigma \quad (17)$$

In a metallic conductor the conduction current will dominate over that caused by the displacement of charges due to the field, so that

$$\mathbf{k}^2 \approx i\omega\mu_0\sigma \quad (18)$$

Using the identity that

$$i^{\frac{1}{2}} = \frac{1+i}{\sqrt{2}} \quad (19)$$

this simplifies to

$$\mathbf{k} = \frac{1+i}{\delta} \quad (20)$$

where

$$\delta = \left( \frac{2}{\mu_0 \sigma \omega} \right)^{\frac{1}{2}} \quad (21)$$

where  $\delta$  is the penetration (or skin) depth. Substituting this back into the monochromatic wave (equation 16) above gives

$$E_y(x, t) = E_{y0} e^{-\frac{x}{\delta}} e^{i(\frac{x}{\delta} - \omega t)} \quad (22)$$

This indicates that the wave attenuates as it travels through a metal in the  $x$  direction with a penetration depth of  $\delta$ . For steel with conductivity of  $10^6$  Siemens per meter and at the frequency of a mobile phone signal (around 1GHz) this gives a penetration depth of the order 10-100 $\mu$ m. The theory in this section was adapted from [1].

It is important to realise that the penetration depth is not the thickness of surrounding material which reduces the electric field to a magnitude of zero, rather it is the characteristic distance over which the magnitude decreases exponentially. An exponential decrease means that the rate of decrease is proportional to the magnitude of the signal with constant of proportionality  $1/\delta$ :

$$\frac{dE_y(x)}{dx} = -\frac{1}{\delta}E_y(x) \quad (23)$$

where  $E_y(x)$  is the maximum wave amplitude as a function of  $x$ , the distance into the metal.

At a distance of  $x = 0$  into the metal

$$e^{-x/\delta} = e^{-0/\delta} = 1 \quad (24)$$

so the amplitude of the wave is not yet decreased. The thickness at which the magnitude will drop to 10% of its original value is given by:

$$e^{-x/\delta} = 0.1 \quad (25)$$

$$-\frac{x}{\delta} = \ln 0.1 \quad (26)$$

$$x = 2.3\delta \quad (27)$$

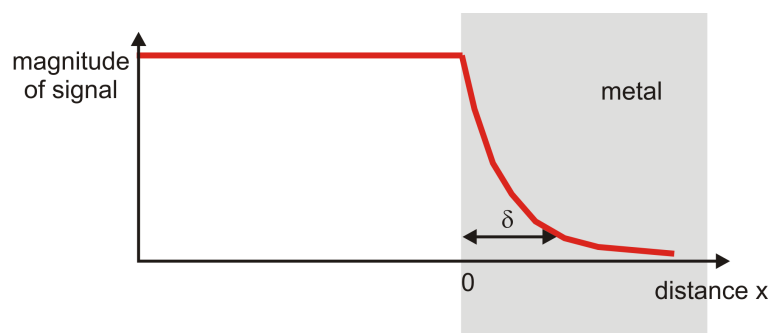
By a similar calculation a drop to a 1% will occur after a distance of  $4.6\delta$  into a metal and to 0.1% after  $6.9\delta$ . See figure 1.

It is not easy to ascertain what electric field magnitude (signal strength) is required for a certain mobile phone to connect to a network - it will depend on the phone. But if we guestimate that it will be between 1% and 0.1% of the original signal magnitude we need a thickness of up to 0.7mm of steel.

In a certain location, the magnitude of the electric field from the local mobile phone mast will depend on environmental and geographical factors as well as which mobile network the phone is connected to.

### 3. Developing an Experiment

A first attempt at demonstrating the Faraday cage using a mobile phone was performed using two empty soup tins pressed together with the phone placed inside. The enclosed phone was dialed from another phone to see if it rang. This method worked fairly reliably with any mobile phone and at any location. I have used this in lessons to demonstrate the behaviour of electromagnetic waves for GCSE pupils (age 14-16 years) and A level pupils (age 16-18 years). An interesting side point is that a metal foil lined bag is sometimes used by shoplifters to prevent security tags on goods setting off alarms as they are smuggled out of shops.



**Figure 1.** The exponential decrease of the magnitude of an electric field inside a conductor



**Figure 2.** Placing a phone in the tin.

For a mobile phone signal the wavelength and frequencies are given in Table 1 for the networks which operate their own base stations in the UK [2].

Note that the 2100 MHz signals listed in [2] for a number of networks is the frequency over which data is sent and not voice calls. The pupils can either be given the above table of frequencies and wavelengths, or if their ability is high enough, they can be asked to find the wavelength for their phone, given the frequency.

Interestingly the Faraday cage still works if there are gaps in the conductor, providing their maximum diameter is ‘significantly smaller’ than the wavelength of the electromagnetic waves. I have developed this into an experiment in which the pupils



**Figure 3.** Phone in the tin, with a textbook to ensure there are no unwanted gaps in the Faraday cage.

Network	Frequency	Wavelength
Orange	1800MHz	17cm
O <sub>2</sub>	900MHz	33cm
Vodafone	900MHz	33cm
T-Mobile	1800MHz	17cm

**Table 1.** Table of mobile phone networks, frequencies and wavelengths in the UK

determine what ‘significantly smaller’, in this case, means. Working in small groups of 2-3, a single tin (opened at one end) is used. When the phone is placed in the tin the open end is covered with metal foil, see figure 2. Sometimes the foil is too thin to totally block the signal (as discussed above) for one or more networks, but this depends on the relative location of the classroom and the mobile phone mast. This ‘failure’ can be turned into a learning opportunity but explaining the situation to the group of pupils and guiding them to use a phone from a different network. A good ‘seal’ is required between the tin, which is upturned on the desk, and the foil which lies on the desk. A text book or two placed on top of the tin usually suffices, see figure 3.

One pupil from the group uses their phone to call the phone in the tin/foil enclosure. Once the pupils have got the phone to fail to ring, they are ready for the next step. A small hole needs to be placed in the foil and the phone tested again to see if it will ring. The hole size then needs to be gradually increased until the phone in the tin starts ringing. The largest ‘diameter’ of the hole is measured each time and is recorded in a table by the pupils along with an indication of whether the phone rang or not.

The final part of the lesson gives the pupils the opportunity to contribute their results to a large table on the board and to discuss and think about their results. The board table has columns for phone network, wavelength, and maximum hole size that

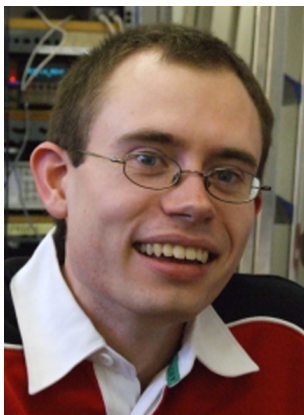
stops the phone ringing.

If there are around 8-10 groups in the class, I have found that I usually get sufficiently good results to draw at least a qualitative conclusion: that the size of the hole can be bigger for the networks with the longer wavelength of radiation. Thus, a mobile phone on a network with a short wavelength (Orange or T-Mobile) will be best if you are trying to use the phone in a lift!

As a further angle of investigation, the location, frequency and network of every phone mast in the UK can be found online [2]. This information may also be available in other countries. In some cases where the mast of a certain network is based on or very close to the school site the examples of Faraday cages described in this article are not effective as the signal strength is too strong. That is, the magnitude of the signal is not sufficiently reduced by the thickness of metal in a piece of foil or a metal can.

#### 4. Acknowledgements

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After completing a PhD at the University of Bristol and a PGCE at Imperial College, Matthew French has recently started teaching physics at Clifton College, Bristol.

#### 5. References

- [1] W. J. Duffin. *Electricity and Magnetism*, pp 350-353 and 371-372. W. J. Duffin Publishing, 2001.
- [2] <http://www.sitefinder.ofcom.org.uk/>.